Particle Accelerators, 1997, Vol. 58, pp. 17–32
Reprints available directly from the publisher
Photocopying permitted by license only

REPORT OF THE WORKING GROUP ON EMITTANCE PRESERVATION

F. WILLEKE *

Deutsches Elektronen Synchrotron, Notkestr. 85, D22603 Hamburg, Germany

(Received in final form 17 March 1997)

The following report is a summary of the working group discussions on emittance preservation and related topics. Experiences from Fermilab, Brookhaven National Laboratory, CERN and DESY have been summarized, compared, and discussed. Progress was reported on high γ_T lattices and novel beam handling techniques. The potential benefit of new accelerators in the CERN PS complex was discussed.

Keywords: Emittance preservation; CERN PS complex

1 OVERVIEW

The working group on emittance preservation consisted of the following members: R. Cappi, CERN; M. Craddock, Triumf; W. Fischer, BNL; B. Goddard, CERN; B. Holzer, DESY; M. Lindroos, CERN; A. Lombardi (scient. Secr.), CERN; P. Martin, FNAL; M. Martini, CERN; C. Moore, FNAL; W. Scandale, CERN; K.-H. Schindl, CERN; H. Schönauer, CERN; G. Schröder, CERN; T. Sen, DESY; L. Vos, CERN; E. Wildner, CERN; F. Willeke, DESY; K. Wittenburg, DESY; V. Ziemann, Svedberg Lab.

The following topics were discussed:

- Emittance dilution effects and efforts to preserve the beam emittance were the main topics of the discussions in the working group. The group compared four proton injection chains and

* Fax: 0049 40 8998 4305. E-mail: willeke@pktr.desy.de.

discussed specific topics on emittance preservation reported by members of the working group.

- The working group discussed the advantages and disadvantages of H^--injection into the circular accelerators compared to the present CERN proton injection scheme into the booster synchrotrons.
- Diagnostics and instrumentation, automated steering and controls which play an important role in preserving the beam emittance have been presented and discussed.
- Transition crossing is critical for preservation of the longitudinal emittance. Emittance blow-up is avoided in high or imaginary γ_T lattices. Several proposals with such lattices have been discussed recently (see for example Ref. 3). In high γ_T lattices, a substantial part of the dispersion function in the bending magnets must be negative. New ways of optimizing such complicated lattices have been proposed and have been discussed during the meeting.
- Two new accelerators for the proton acceleration chain at CERN have been proposed to more easily achieve or even to exceed the beam brightness requirements of the LHC. The virtue of a superconducting LINAC made from the LEPII superconducting rf equipment and a new circular accelerator which would replace the PS have been presented and discussed.

2 LHC BEAM BRIGHTNESS REQUIREMENTS

The beam brightness requirements on the LHC beams are quite demanding. In order to push the beam brightness up to limitations which might occur due to beam–beam effects, component heating and coherent instabilities in the LHC with its large beam energy ($E_{\mathrm{beam}} = 7\,\mathrm{TeV}$), its complicated beam pipe designs like the so-called beam screens, its careful minimization of impedances and the design of powerful damper systems to control coherent instabilities and blow-up,[1] a high brightness beam from the injectors is required. For this reason, the achievable luminosity

$$\mathcal{L} = \frac{\gamma}{4\pi e} \frac{N_{\mathrm{p}}}{\varepsilon_{\mathrm{N}}} \frac{I_{\mathrm{p}}}{\beta^*} \tag{1}$$

TABLE I LHC beam brightness requirements

	Nominal parameters	*Ultimate parameters*
Particles per bunch	$1.0 \cdot 10^{11}$	$1.6 \cdot 10^{11}$
Normalized transverse emittance	$3.75\,\mu m$	$3.75\,\mu m$
β-function at IP	$0.5\,m$	$0.5\,m$
Beam current	$0.5\,A$	$0.8\,A$
Luminosity	$1.0 \cdot 10^{34}\,cm^{-2}\,s^{-1}$	$2.5 \cdot 10^{34}\,cm^{-2}\,s^{-1}$

(γ is the relativistic factor, N_p is the number of protons per bunch, ε_N is the normalized transverse emittance which is assumed to be the same in both planes, I_p is the total proton beam current, β^* is the beta function at the interaction point (IP)) of the LHC will depend on a high beam brightness N_p/ε_N. The LHC design report quotes a nominal scheme with a luminosity of $\mathcal{L} = 1.0 \cdot 10^{34}\,cm^{-2}\,s^{-1}$. While the beam brightness requirements for the nominal scheme are already quite ambitious, the so-called ultimate scheme requires an additional increase in beam intensity to achieve a luminosity of $\mathcal{L} = 2.5 \cdot 10^{34}\,cm^{-2}\,s^{-1}$. Furthermore, the dynamic aperture in the LHC at injection is very tight as well. Beam brightness cannot be gained at the expense of a blown-up beam emittance. This implies tight emittance budget in the proton acceleration chain. The LHC brightness requirements[2] are referenced in Table I. In the beginning of the acceleration chain, at injection into the CERN-PS Booster, β-tron stacked proton bunches with a transverse normalized emittance of $\varepsilon_N = 2.7\,\mu m$ and an intensity of $1.7 \cdot 10^{11}$ protons per bunch (N_p) are available. In order to meet the LHC requirements, the emittance blow-up which can be allowed during acceleration and transfer in each of the three acceleration steps Booster–PS–SPS is only 11.6%. In the ultimate scheme, this tight emittance budget must be met with a full intensity beam which means that there is very little margin for degradation of the beam brightness N_p/ε_N in the acceleration chain. Therefore all possible sources of dilution and blow up must be identified and removed.

3 COMPARISON OF PROTON ACCELERATION CHAINS

The working group discussed and compared four different proton injection chains with respect to beam brightness, acceleration and transfer efficiency and beam dilution:

- the AGS acceleration complex at Brookhaven National Laboratory, with a 200 MeV H^--LINAC, a 1.5 GeV/c booster and a 30 GeV/c AGS synchrotron,
- the PS complex as injector for the LHC, with a 50 MeV H^+-LINAC, the low energy 1.4 GeV/c booster with four rings and the 26 GeV PS synchrotron,
- the Tevatron injection complex at Fermilab, with a 400 MeV H^--LINAC, the 8 GeV/c booster, and the large main ring synchrotron operated up to 150 GeV/c.
- the HERA injection complex at DESY with a 50 MeV H^--LINAC, the DESY III 7.5 GeV/c synchrotron and the PETRA storage ring with a maximum energy of 40 GeV.

The relevant parameters for the beam brightness budget have been identified as: the beam energy at injection E_{inj}, the number of particles per bunch N_{p} and number of bunches N_{b}, the normalized emittance ε_{N}, the bunch spacing τ_{b}, the longitudinal emittance ε_{s}, a simplified expression for the space charge tune shift $\Delta Q = N_{\text{p}} N_{\text{b}} r_{\text{p}} / (4\pi B_{\text{f}} \beta \gamma^2 \varepsilon_{\text{N}y}(1 + \sigma_x/\sigma_y))$ (where β, γ are the relativistic factors, r_{p} is the classical proton radius and B_{f} is the ratio between mean and peak beam current). An overall parameter for the transverse beam brightness suited for the comparison has been defined as

$$B_{\text{B}} = \frac{N_{\text{p}}}{10^{10}} \frac{\varepsilon_{\text{N}}}{\mu\text{m}} \frac{\varepsilon_{\text{s}}}{\text{eV s}}. \tag{2}$$

The results of this comparison are summarized in Tables II–V.

The four systems are very different. The CERN system is the only system which does not use H^- multiturn injection but β-tron stacking. The 50 MeV LINAC proton beam is injected into the small pre-booster rings to avoid limitations by space charge. FERMILAB and BNL avoid space charge limitations by high energy LINACs ($E_{\text{kin}} =$ 400 and 200 MeV, respectively). DESY has to manage with a 50 MeV H^--LINAC beam to be injected into the booster with 300 m circumference.

The advantage of the PS injection complex is the powerful low energy CPS booster with four rings. At injection into the booster, the

TABLE II The AGS complex

	End Linac	*Booster Flat B.*	*Booster Flat Top*	*Synchrotron Flat B.*	*Synchrotron Flat Top*
Particles	H^-	H^+	H^+	H^+	H^+
Momentum/(GeV/c)	0.64	0.64	1.5	1.5	30
Circumference/m		202	202	807	807
Bunch intensity/10^{10}	30 mA	1340	1125	840	800
Bunch spacing/ns (@ $v=c$)		600	360	360	360
$\varepsilon_N^{\mathrm{hor}}/\mu\mathrm{m}$	1.5	7.0	7.5	8.5	15
$\varepsilon_N^{\mathrm{ver}}/\mu\mathrm{m}$	1.5	7.0	7.5	8.5	15
Energy spread/kV	1100				
ε_s/eV s		1.1	1.5	3.0	13
B_B		174	100	33	4.1
ΔQ		0.50	0.30	0.72	0.005
B_B-dilution factor	42				

TABLE III The TEVATRON injection complex

	End Linac	*Booster Flat B.*	*Booster Flat Top*	*Synchrotr. Flat B.*	*Synchrotr. Flat Top*	*Synchrotr. coalesced*
Particles	H^-	H^+	H^+	H^+	H^+	H^+
Momentum/(GeV/c)	0.95	0.95	8.0	8.0	150	150
Circumference/m		474	474	6281	6281	6281
Bunch intensity/10^{10}	(40 mA)	6	5	4.5	4.0	30
Bunch spac./ns ($v=c$)		19	19	19	19	133
$\varepsilon_N^{\mathrm{hor}}/\mu\mathrm{m}$	1.1	2.5	2.0	2.0	2.0	2.0
$\varepsilon_N^{\mathrm{ver}}/\mu\mathrm{m}$	1.1	2.5	2.0	2.0	2.0	2.0
Energy spread/kV	100					
ε_s/eV s		0.01	0.01	0.01	0.012	0.36
B_B		300	250	225	167	42
ΔQ		0.17	0.008	0.104	0.0053	0.0036
B_B-dilution factor	5.8					

brightness is only moderate ($B_B=64$) due to the H^+-injection scheme. The injectors, however, are well staged in energy and the beam is accelerated in this complex with only little dilution ($B_B=16.8$). Dilution occurs in the longitudinal phase space only at high energy due to a rebucketing procedure from 8 to 84 bunches in order

TABLE IV The LHC injection complex

	End Linac	*Booster Flat B.*	*Booster Flat Top*	*Synchrotr. Flat B.*	*Synchrotr. Flat Top*	*Synchrotr. rebunched*
Particles	H^-	H^+	H^+	H^+	H^+	H^+
Momentum/(GeV/c)	0.31	0.31	2.14	2.14	26	26
Circumference/m		157	157	628	628	628
Bunch int./10^{10}	(160 mA)	170	170	170	170	17
Bunch spac./ns ($v=c$)		260	260	260	260	25
ε_N^{hor}/μm	1	3.5	3.5	2.7	2.7	2.7
ε_N^{ver}/μm	1	2.0	2.0	3.0	3.1	3.1
Energy spread/kV	75					
ε_s/eV s		1	1	1.4	1.4	0.35
B_B		64.2	63.4	42.7	42.0	16.8
ΔQ		0.25	0.026	0.25	0.004	0.004
B_B-dilution factor	3.83					

TABLE V The HERA injection complex

	End Linac	*Booster Flat B.*	*Booster Flat Top*	*Synchrotron Flat B.*	*Synchrotron Flat Top*
Particles	H^-	H^+	H^+	H^+	H^+
Momentum/(GeV/c)	0.31	0.31	7.5	7.5	40
Circumference/m		318	318	2394	2394
Bunch intensity/10^{10}	(12 mA)	15	11	9	8
Bunch spacing/ns (@ $v=c$)		96	96	96	96
ε_N^{hor}/μm	0.8	2.5	5	6	8.7
ε_N^{ver}/μm	0.3	1.3	3	5	6.3
Energy spread/kV	60				
ε_s/eV s		0.07	0.08	0.09	0.1
B_B		115.5	35.5	18.25	10.8
ΔQ		0.37	0.0016	0.0016	0.0004
B_B-dilution factor	10.5				

to provide the optimum bunch spacing and bunch population for the LHC. The brightness is then only 30% of the original value.

In the case of FNAL a very high brightness beam ($B_B = 300$) is achieved in the booster using the high energy LINAC with $E_{kin} =$ 400 MeV. The large brightness comes from the small longitudinal emittance due to a small energy spread of the LINAC beam. This provides a large margin in longitudinal emittance, which is used up by the coalescing process in the main ring at high energy. Eleven bunches are coalesced into a single bucket which provides the high bunch intensity for $p\bar{p}$ collisions in the TEVATRON. The bunch intensity is increased by a factor of seven at the expense of an increase of the longitudinal emittance of thirty which includes strong dilution effects during rf manipulations. Due to the high injection energy in every machine, space charge effects are quite moderate and despite the large overall dilution, the remaining beam brightness at the end of the acceleration chain is still very good ($B_B = 42.7$).

In the case of AGS, the beam is used for fixed target experiments and the beam emittance is not very relevant. The acceleration chain is optimized for high intensity. This gives a high brightness beam at injection into the booster ($B_B = 174$). The emittance, however, is blown up deliberately to avoid intensity losses later in the AGS. This explains the large dilution factor of more than forty ($B_B = 4$).

The HERA injection chain faces the most difficult conditions. The 50 MeV H^--LINAC provides a high-brightness beam at injection ($B_B = 115$) into the DESYIII synchrotron. But due to large space charge forces at the low injection energy in conjunction with a slow acceleration cycle in DESYIII and PETRA, the dilution factor is about ten ($B_B = 11$). A special requirement of HERA is a small longitudinal emittance. Proton bunches must be as short as possible for the collisions with a 8 mm long electron bunch. Therefore, it is not possible to gain a brighter beam in the transverse plane by coalescing or rebucketing procedures which would lead to a blow-up of the longitudinal emittance. It might be possible to improve on brightness of the HERA beam by compensation of nonlinear resonances in the DESYII booster synchrotron which is planned but not yet done.

This comparison shows that the achieved beam brightness and the corresponding dilution factor reflect the effort invested in the low energy injectors. The injection chain with the highest energy LINAC delivers the brightest beams. In the CERN case, the booster synchrotron with its small circumference helps to master space charge effects. In the low injection energy machines, a large effort is necessary to minimize space charge effects by controlling the working point of the machine during the acceleration cycle in a complicated way.

Compensation of nonlinear fields and control of coupling appears to be essential.

A particular aspect of this comparison is the benefit of H^- injection. At Fermilab (report by Holmes[4]), H^- injection allows to reach the space charge limit at 400 MeV kinetic energy in the booster with a moderate LINAC current of 30 mA (which is essential to provide the large margin in longitudinal emittance needed later in the coalescing process). Ten to fifteen turns with $4 \cdot 10^{11}$ protons each are injected and captured adiabatically in 84 buckets. The stripping foil is made of carbon with $200\,\mu g\,cm^{-2}$. The stripping efficiency is very good and there is little emittance blow up in the foil. Foil lifetime is not causing any problems. With the present parameters, the threshold of magnetic stripping in the kicker magnet is not reached. The injection efficiency is 70%. The conclusion is that the H^- injection scheme is certainly an advantage and an important factor for the delivery of the high brightness beam of the TEVATRON.

At the Brookhaven AGS (report by Weng[5]), the change from H^+ to H^- helped to reduce the current in the 200 MeV LINAC from 65 to 30 mA. More than 100 turns are injected to achieve an intensity of $1.8 \cdot 10^{13}$ in the AGS. The injection efficiency went up at the same time from 55% to 85%. The radiation dose for components in the injection area was reduced by a factor of at least five. The conclusion is that the H^- injection has clear advantages for the high current operation of the AGS.

At DESY (report by Maidment[6]), the H^- injection from a 50 MeV LINAC into DESYIII allows to exceed the space charge limit with a ten-turn injection with a LINAC current of only 14 mA. This corresponds to an intensity of $2 \cdot 10^{12}$ which is adiabatically captured in 11 bunches. The stripping foil is carbon ($80\,\mu g\,cm^{-2}$). The stripping efficiency is good. There are no problems with the lifetime of the foil. To reach the same current with H^+ injection, the LINAC current would have to be increased considerably with corresponding increase in energy spread and longitudinal emittance. The DESYIII experts are convinced that H^- injection is a clear advantage for the brightness of the HERA beams.

The result of this comparison is that H^- injection works well in each case. There are no technical problems with the injection scheme which are all very similar. Sources have sufficient intensity and stability. There are no problems with the lifetime of the stripper foil. H^- injection might also be an advantage for the LHC injection chain.

4 EMITTANCE DILUTION ISSUES

Strategies to control emittance blow up have been discussed and two extreme positions have been identified.

- *The Systematic Route:* Sources of mismatch should be clearly identified and eliminated systematically. An understanding of the beam optics to high precision is very important. A lot of effort has to be invested in order to improve the model of the delivering and the receiving machine and the connecting beam line. This involves careful measurements of magnetic fields, including edge field, fringe fields, stray fields and eddy current effects. It also requires a large effort in beam instrumentation, sophisticated software for the analysis of measurements and beam time to provide the necessary information. A good example is the effort made to model correctly the magnetic fields seen by the beam and the corresponding beam optics in the extraction trajectory from the PS synchrotron.[7]
- *The Fast Route* is to feedback directly from measured beam dilution effects to correction elements. This requires sometimes novel and dedicated diagnostic devices. A good example for this route is the empirical correction of β-tron mismatch in the CERN AA-ring by using a quadrupole pick-up.[8] Other examples are the use of transverse and longitudinal damper systems to damp injection oscillations. Good support by sophisticated operation programmes is important here. Another important aspect is that empirical correction of errors needs to be performed in routine operation. The necessity to automatize routine correction procedure is often essential.

In real accelerators both routes are usually pursued in parallel to control the emittance dilution effectively. A majority of the working group participants, however, had a preference for the systematic route.

The identification of sources of emittance dilution is often not a topic of fundamental beam physics but has usually to do with hidden imperfection of complex systems which are difficult to identify. Several such examples have been presented in the working group:

- correct treatment of edge focusing of strong bends in the different extraction lines of the four CP-booster rings,[9]
- correct modelling of end fields in the PS extraction path,[7]
- identification of rolled quadrupole magnets in the TEVATRON as a strong source of dilution,[11]
- improvement of kicker flat top ripple in the SPS,[12]
- optimized rf voltage programs to control intrabeam scattering in RHIC,[10]
- detailed discussions of a long list of improvements in the SPS to avoid dilution.[13]

These are part of these proceedings and shall not be described in detail in this summary.

Important in this context are also improved controls and beam handling which will be discussed below. Good knowledge of the beam optics and a quantitative understanding of its deviations from the linear machine model and sources of imperfections is a crucial aspect of emittance preservation. A novel scheme to check on beam optics by using beam position monitors has been reported[14] and discussed in the working group. The method consists of the comparison of the theoretical sensitivity S_{ij} of beam orbit changes at the beam position monitors δx_i due to changes of the corrector magnets $\delta\theta_j$, $S_{ij} = \delta x_i/\delta\theta_j$, with measured values. Distortions of theoretical senitivity matrix S due to potential sources of errors g_k (such as error in calibration factors, unknown magnet defects like shorts, ground faults, stray fields, temperature and saturation effects, etc.) can be expanded in Taylor series in these parameters:

$$\Delta S = \sum \frac{\partial S}{\partial g_k} \cdot \delta g_k + \text{higher order.} \tag{3}$$

The first-order expansion coefficients $\partial S_{ij}/\partial g_k$ can be easily evaluated by linear beam optics calculations. The discrepancies between model sensitivity and measured sensitivity ΔS_{ij} are inserted into the Equation (3) and the equation can be solved for any number of errors $k_{\max} < i_{\max} \cdot j_{\max}$. This method provides a very useful tool especially for smaller machines. It will be extremely useful to test for suspicious accelerator elements and could save considerable time in trouble shooting.

5 DISCUSSION ON PROGRESS IN CONTROLS AND MACHINE HANDLING

Large accelerators with low injection rates need a sophisticated control system for efficient optimization of beam injection in order to control the beam brightness. In small accelerators with frequent injection, this appeared not to be necessary. Considering the stringent need for beam brightness preservation in the LHC injector chain, however, more advanced techniques have to be introduced into the smaller accelerators as well. A large effort has been started for the PS and PS Booster machines to automatically correct on-line for injection steering errors, energy and phase mismatch at injection, and beam envelope mismatch at injections. Tools are being provided to measure machine optics parameters automatically as part of routine procedures. Details about the implemented data structure, the programming tools which have been provided and first implementation have been reported and will be published in these proceedings.[20,17,18]

6 HIGH γ_T-LATTICES

Lattices with high or imaginary value of the transition energy are a way to prevent transition crossing and the corresponding difficulties with beam stability and longitudinal emittance dilution. Another advantage of such lattices is that the transition energy can be adjusted easily close to injection- or extraction energy to help bucket matching and other rf manipulations.

The concept of such lattices is the following: Consider an arc which is composed of identical subsections. The periodic dispersion of these subsections is distorted by a missing magnet or another modulation of the regular bend field structure or by modulations of the lattice functions. The phase advance of the subsections can be tuned such that the average value of the dispersion in the dipole magnets becomes negative.

If the variation is produced by a missing magnet, this can easily be seen: Consider a structure of N FODO cells of a length L with a missing magnet. The periodic dispersion of the FODO cell is (approximately)

$$D_{\text{cell}} \simeq \beta\theta \cdot \frac{1+\cos(\Delta\phi/2)}{2\sin(\Delta\phi/2)}. \tag{4}$$

($\Delta\phi$ is the phase advance of the FODO-cell, β is the β-function in the middle of the dipole and θ is the bend angle.) A missing magnet adds a dispersion wave to the periodic dispersion

$$D_i^{\text{beat}} \simeq -\beta\theta \frac{\cos((i-N)\Delta\phi/2)}{2\sin(N\Delta\phi/2)} \tag{5}$$

($i = \{0, \ldots, N-1\}$). Let the phase advance of the cell be $N\Delta\phi = 2n\pi + 2\delta$, where n is an odd integer. The contribution to the momentum compaction factor $\alpha = 1/\gamma_{\mathrm{T}}^2$ is then given by

$$\alpha = \int_0^{NL} \mathrm{d}s\, D(s)/\rho \simeq \frac{1}{2}\frac{\theta^2\beta}{N \cdot L} \cdot \frac{1+2(N-1)\cot(\Delta\phi/4)\,\delta}{\delta}. \tag{6}$$

The momentum compaction factor becomes thus negative if

$$\delta \simeq -\frac{1}{2(N-1)\cot(\Delta\phi/4)} \tag{7}$$

and the momentum compaction factor α can be easily tuned by small changes in δ. The peak value of the dispersion is in the order of $D_{\text{peak}} = \beta\theta/(4\delta)$. Delta is in the order of $\delta = 0.2$ which means that the dispersion is enhanced by a factor of three to five beyond its "natural" value.

Variation of the focusing strength can be used to reduce the dispersion wave at the expense of some β-beating. For the corresponding tedious optimization procedure, a new method of representing such lattices has been presented[15] and discussed in the working group. The method exists in expanding all the focusing and bending fields in

Fourier series and restricting the evaluation to leading or quasi "resonant" terms. This provides a closed form for the dispersion function also for the case of a modulated focusing field. The details will be given by a contribution to these proceedings.[15]

7 DISCUSSION ON A NEW PS-TYPE ACCELERATOR

Ideas on a new synchrotron that would replace the PS have been presented[16] at the workshop. This has been discussed in the working groups. The main features of this new accelerator would be a more effective magnet structure with smaller magnet gaps which would increase the injection energy of the SPS to 32 GeV. At the same time the energy consumption of this machine would be smaller than the present one of the PS. The lattice would have an imaginary transition energy. It might be possible to build such a machine without sextupole magnets. The focusing would be stronger, the beam envelopes smaller. Transient beam loading effects in the SPS would be reduced and the present complicated rf scheme in the PS would become more simple so that there is less dilution of the beam brightness.

The working group discussed the possible benefit of this accelerator with the result that there is no doubt that the new machine would have many advantages and would allow to meet the LHC design goal more safely and more reliably. However, it is not obvious whether these benefits are large enough to justify the costs of building such a machine, particularly in view of the fact that there are no serious concerns that the present injector chain would not be able to deliver the bright beams for the LHC. There are further disadvantages concerning machine operations during the construction period. Furthermore, one has to take into account the time which is necessary to bring up such a new accelerator to full performance.

8 DISCUSSION ON A SUPERCONDUCTING PROTON LINAC

After the end of the LEPII physics programme at the beginning of installation of the LHC in the year 2000, the large LEPII inventory in superconducting rf structures and rf power converters becomes available. A proposal has been discussed to make use of these components to build a powerful 2 GeV H^--injector LINAC for the LHC proton acceleration chain.

This new injector would provide very bright H^- beams for injection at 2 GeV kinetic energy into the CPS. The emittance would be as small as 0.8π mrad mm (normalized, one σ). One LINAC pulse would deliver up to $3 \cdot 10^{13}$ particles and would allow to fill the PS until the space charge limit is reached using charge-transfer injection by a stripper foil. The system would be composed of 68 cryogenic modules with four superconducting 4-cell 350 MHz cavities each. In every module an accelerating voltage of 40 MV would be generated. This allows a total beam energy of 2 GeV. In order to accelerate a beam of 10 mA pulsed beam current, a power of 45 MV has to be provided. The beam pulse would be 500 μs long. The repetition rate could be 0.8 Hz. The rf coupling would be reduced somewhat compared to the present operation mode of the system in LEP. This allows to run in the $3\pi/2$-mode which provides some 6 MV m^{-1} accelerating voltage. The synchronous beam phase is 30°.

The system would begin with an H^- source followed by an rf quadrupole. After a fast chopper the beam would be injected into the present 50 MeV Alvarez-type drift tube LINAC. This is followed by two room-temperature high gradient structures to accelerate the beam to 150 and 300 MeV, respectively. At this point the beam will be injected into two staged superconducting structures which accelerate the beam to 2 GeV. The whole injector would be 1500 m long.

Many technical details for such a machine still need to be clarified. The most important question is whether it is possible to operate the klystrons in pulsed mode using the modulation anode. There are many more technical issues. For more details see Ref. 9.

The working group discussed the potential benefit for the LHC from such a powerful injector. The brightness of the beam at injection into the PS will be nominally increased by a large factor. A naive scaling of the beam brightness parameters is shown in Table VI. The potentially small emittance due to the small LINAC beam emittance could be very advantageous for injection into the limited aperture of the LHC. However, one has to take into account the possible emittance blow-up during multiturn injection with more than 100 turns.

TABLE VI Scaled beam brightness parameters with a 2 Gev LINAC

	End Linac	*Synchrotr. Flat B.*	*Synchrotr. Flat Top*
Particles	H^-	H^+	H^+
Momentum/(GeV/c)	2.78	2.78	26
Bunch int./10^{10}	(10 mA)	20	20
Bunch spac./ns ($v=c$)		25	25
ε_N^{hor}/μm	1	2.0	2.0
ε_N^{ver}/μm	1	2.0	2.0
Energy spread/kV	75		
ε_s/eV s		0.1	0.1
B_B		100	100
ΔQ		0.27	0.006
B_B-dilution	1.00		

An advantage of the scheme would be that the PS beam could be captured adiabatically in the final rf structure at injection. The complicated rebucketing procedure with a large blow up in the longitudinal emittance could be avoided. This provides the largest contribution to the increase in the final beam brightness of the LHC beam which then would be $B_B = 100$. The corresponding small momentum spread is another potential advantage for single particle stability at injection into the LHC. Possible collective beam instabilities, however, need to be investigated in order to estimate to what extent the potential increase in beam brightness can be exploited.

Considering the fact that a modest increase of the injection energy into the booster from 50 to 100 MeV would already increase the beam brightness by a factor of 1.5, providing sufficient margin for the ultimate LHC scenario, it is not obvious that the LHC need for bright beams justifies the construction of such a large machine.

9 CONCLUSION

The meeting united experts from different proton accelerator laboratories, from large and from small accelerators to discuss the issue of emittance preservation. The discussions have been a very fruitful exchange of ideas and experiences. The working group arrived at the conclusion that the demanding need for beam brightness of the LHC can be satisfied by the LHC injector change as it is at present.

References

[1] P. Lefevre and T. Pettersson (eds.), *The Large Hadron Collider, Conceptual Design*, CERN/AC/95-05 (1995).
[2] J. Gareyte, Requirements of LHC on its injectors, these proceedings.
[3] Y. Mori *et al.*, Synchrotron design issues of the Japanese Hadron Project, *Proceedings of the EPAC96*, Barcelona (1996), p. 569.
[4] S. Holmes, working group presentation.
[5] B. Weng, working group presentation.
[6] J. Maidment, working group presentation.
[7] M. Martini, Trajectory and optical parameters in a non-linear stray field, working group presentation.
[8] F. Pederson, working group presentation.
[9] M. Lindroos, Mismatch between the PSB and CPS due to the present vertical, these proceedings.
[10] W. Fischer, Emittance growth in RHIC during injection, these proceedings.
[11] C. Moore, Emittance dilution in transfers from the main ring to the tevatron, these proceedings.
[12] G. Schroeder, working group presentation; E. Vossenberg, Kicker magnet upgrading for SPS operating as LHC injector, these proceedings.
[13] L. Vos, Preservation of emittance of the LHC beam in the SPS, these proceedings.
[14] V. Ziemann, Debugging real accelerators, these proceedings.
[15] V. Senichev, working group presentation.
[16] B. Autin, A new proton synchrotron for the LHC injector, these proceedings.
[17] E. Wildner, working group presentation.
[18] M. Martini, working group presentation.
[19] R. Garoby, working group presentation.
[20] B. Autin, Automatic beam steering and emittance preservation in the PS complex, these proceedings.